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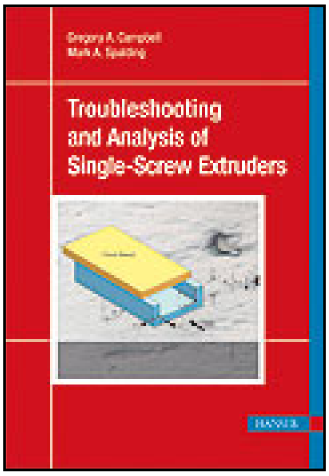

Preface

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Analyzing and Troubleshooting Single-Screw Extruders

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Preface

Classically, all prior extrusion books are based on barrel rotation physics. Literature developed over the past 15 years has led to this first book to be published based on the actual physics of the process—screw rotation physics. After the theories and the math models are developed in the first nine chapters, the models are then used to solve actual commercial problems in the remainder of the book. Realistic case studies are unique in that they describe the problem as viewed by the plant engineers and provide the actual dimensions of the screws. Knowledge is developed using a series of hypotheses that are developed and then tested, which allows a series of technical solutions. Several actual solutions are proposed with the final results that solve the problem then clearly presented. Overall, there is not a book on the market with this level of detail and disclosure. New knowledge in this book will be highly useful for production engineers, technical service engineers working with customers, consultants specializing in troubleshooting and process design, and process researchers and designers that are responsible for processes that run at maximum rates and maximum profitability.

Debugging and troubleshooting single-screw extruders is an important skill set for plant engineers since all machines will eventually have a deterioration in their performance or a catastrophic failure. Original design performance must be restored as quickly as possible to mitigate production losses. With troubleshooting knowledge and a fundamental understanding of the process, the performance of the extruder can be restored in a relatively short time, minimizing the economic loss to the plant. Common root causes and their detection are provided. Hypothesis testing is outlined in Chapter 10 and is used throughout the troubleshooting chapters to identify the root causes. Elimination of the root cause is provided by offering the equipment owner several technical solutions, allowing the owner to choose the level of risk associated with the process modification. Mechanical failures are also common with single-screw extruders, and the common problems are identified. Illustrations are provided with the problems along with many numerical simulations of the case studies. Collectively, these instruct the reader on how to determine and solve many common extrusion problems. About 100 case studies and defects are identified in the book with acceptable technical solutions. Lastly, we

hope that this book provides the information and technology that is required for the understanding, operation, and troubleshooting of single-screw extruders.

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Mark A. Spalding

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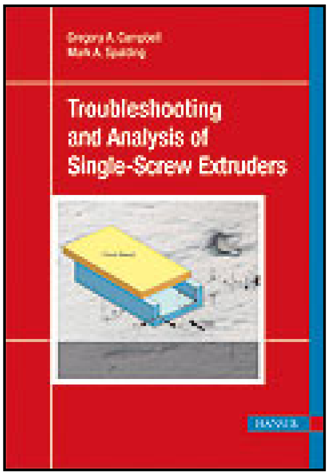

Sample Pages

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12 Flow Surging

Flow surging is defined as the oscillatory change in the rate of the extruder while maintaining constant set point conditions. Flow surging can originate from many different sources including improper solids conveying, melting instabilities, flow restrictions, and improper control algorithms [1–5]. Surging in most cases results in lower production rates, higher scrap rates, higher resin consumption, material degradation, and higher labor costs. In mild cases, flow surging will cause plant personnel to set the product at the low end of the dimension setting at the low rate portion of the surge. At the high rate portion of the surge, the dimensions of the product will be oversized. Oversized products will use more resin than necessary, adding cost to the product and decreasing the profitability of the plant. Obviously, a process that is very steady has the capability of minimizing resin usage and thus maximizing the profitability of the process. For a profile process where the dimension of the cross section is critical to downstream assembly processes, the extreme ends of the rate surges may result in a product that is outside of the specification, and some profiles will need to be scrapped or recycled. In this chapter numerous case studies along with diagnostic methods are presented for processes that flow surge.

The additional cost of producing products from a line that is flow surging can be substantial. If the flow surge is not too large and the line can be operated, the instability of mass flow at the die can cost the converter from 5 to 15% added costs in resins. The higher resin costs are incurred because the dimensions of the articles are larger or thicker than needed. For example, if a line is producing sheet for a downstream thermoforming process and it is operating unstably, then some thermoformed parts will have an acceptable mass while others will have a higher mass, costing the plant more in resin. Often the instability occurs only at a high rate while at lower rates the process is stable. In this case the plant may miss shipment dates since the line can only be operated at a fraction of its capacity, or the plant may incur higher labor costs because the line will need to operate over weekends. In severe cases, flow surging can cause the line to be incapable of producing product at any rate. Thus, in order to produce product at the lowest possible cost, the line must be operating stably so that the rate and product quality are maximized.

Processes that flow surge will often cause a higher level of degradation products to occur in the extrudate. For these cases, the unsteady nature of the flows in the screw channels will tend to break off small levels of degradation products adhering to the screw. The degradation products could occur at the flight radii and regions with long residence times, and they may not contaminate the extrudate under normal conditions. But the unsteady-state nature of the flow surge will tend to break them away from the screw surface.

12.1 An Overview of the Common Causes for Flow Surging

Improper process temperatures and poor temperature controls are common root causes for flow surging. For example, solids conveying depends on a balance of the forwarding forces at the barrel wall and the pushing flight and the retarding forces at the screw surface. These forces depend mainly on the geometry of the channel and are directly proportional to the coefficient of dynamic friction for temperatures less than the melting (or devitrification) temperature and on viscous forces for higher temperatures [6]. Since the coefficient depends on temperature, pressure, and velocity [7], surface temperature changes for the barrel and screw in the feeding section will strongly affect the performance of the extruder. If the surface temperatures become too different from the optimal values, flow surging and loss of specific rate will occur. If the solids-conveying section of the extruder is controlling rate, not the metering section as designed, then a portion of the screw channel between the sections will be partially filled at the low-rate swing of the cycle and most often will be completely filled at the high-rate region of the cycle.

Improper design and operation of the melting section of the screw can lead to extrusion instabilities. For example, solid bed breakup [3] can cause solids to migrate downstream. These solids can wedge into other sections of the screw and cause the extruder to flow surge [2, 4] or cause the extrudate to have periodic changes in temperature. Periodic changes in discharge temperature will cause some level of flow surging at the die [8].

12.1.1 Relationship Between Discharge Pressure and Rate at the Die

Dies are shaping devices that operate at a rate that is directly proportional to the upstream pressure. Thus, if the pressure to the die is not constant then a variable rate will occur at the die opening, causing the dimensions of the product to vary. Rate surges at the die can be estimated from the pressure surges using the

following equations for flow through a cylindrical restriction (or die) for a power law fluid [4]:

$$\Delta Q = (Q_1 - Q_2) / Q_1 = 1 - (1 - \Delta P)^{1/n} \tag{12.1}$$

$$\Delta P = (P_1 - P_2) / P_1 \tag{12.2}$$

$$\text{or} \quad \frac{Q_1}{Q_2} = \left(\frac{P_1}{P_2}\right)^{1/n} \tag{12.3}$$

where n is the power law index, Q_1 and P_1 are the rate and discharge pressure at condition 1, and Q_2 and P_2 are the rate and pressure at condition 2. The pressure at the die lip is assumed to be zero. For example, a 5 % variation in the discharge pressure (ΔP = 0.05) for a polymer with a power law index of 0.3 will cause a 16 % change in the instantaneous rate (ΔQ = 0.16). An instantaneous rate change of this magnitude is unacceptable for most processes. The flow relationship with pressure is much more complicated than this for a commercial die, but the trend is the same.

12.2 Troubleshooting Flow Surging Processes

The analysis and troubleshooting of a process that is flow surging can be a difficult task, especially when the line is required to run production. The analysis can often be complicated by the operation of equipment downstream from the die. For example, if a pulling system is not operating at a constant speed then variations in velocity can cause the product to vary in dimension even though the extruder is operating stably. Worn components on a calendering roll stack can cause the speed of the rolls to vary or cause the gap between the rolls to change during a revolution. Both conditions will cause the product to change dimensions in the downstream direction. Unit operations downstream from the die must be checked to determine if they are the root cause of the product variation. The troubleshooter must be diligent to set a hypothesis and then test the hypothesis. If some problem other than the root cause is fixed, then the process will continue to flow surge.

The standard array of diagnostic equipment is required for the troubleshooting of a process that is flow surging. These tools include screw measuring devices, pyrometers, and devices to calibrate sensors in the process. These devices are discussed in Chapter 10. Often it is very difficult to impossible to determine a cause and effect relationship from process displays that are attached to typical extrusion

lines. However, a portable data acquisition system that is capable of collecting process data as a function of time is highly useful in determining the cause and effect relationships between process parameters. In all of the cases presented here, the extrusion line was either equipped with a data acquisition system or a temporary acquisition system was connected to the machine during the trial.

12.3 Barrel Zone and Screw Temperature Control

Improper selection of process temperatures, poor temperature control, and inoperative temperature control devices are common causes for flow surging. As stated earlier, temperatures for the metal surfaces in the solids-conveying zone must be within a specific range for an application. This temperature range will depend on the resin, equipment design, placement of the temperature control sensor, and rate. Thermocouple placement on extruders is not standard, and thus they can be positioned at different axial positions for the zones and at different depths into the barrel wall. Because of these extruder and process differences, barrel temperatures typically need to be optimized for the machine and application. Optimization of barrel temperatures was presented in Section 10.9.

Equipment devices that are not functioning properly can cause a process to flow surge. For example, the feed casing of the extruder is typically cooled with water such that the outside temperature of the casing is about 50 °C or less. If the cooling water flow is turned off or is not flowing at a high enough rate, then the temperature of the inside wall of the casing will become too hot to convey solids into the machine. As a general rule for most resins, the outside temperature of the feed casing will be too hot to touch if the inside wall becomes too hot to convey solids, that is, at temperatures higher than 50 °C. At high casing temperatures, the rate-limiting step of the process is the solids conveying of resin from the casing to the barrel and not the metering channel of the screw. Thus, the specific rate will decrease and flow surging is very likely to occur. For specialty PE resins with very low solid densities, the temperature of the feed casing may need to be less than 35 °C. High temperatures on the feed casing can also cause the resin to bridge over the feed opening such that pellet flow to the extruder is severely or completely restricted.

Flow surging can occur if the temperature of the screw becomes too high in the solids-conveying section. In general, the temperature of the screw in this section needs to be less than the T_g for amorphous resins or less than the melting temperature for semicrystalline resins. Small-diameter screws will typically operate at feed

zone screw temperatures that are low enough without the need for special cooling. For screws 150 mm in diameter and higher, the temperature of the screw, however, can become too hot for optimal solids conveying. In these cases, the temperature of the screw can be decreased by flowing water into the screw using a rotary union and piping assembly, as shown in Fig. 12.1. Cool process water flows through the union and into a pipe that extends up to within 10 cm of the end of the cooling hole. The water then flows back out of the screw through a section of cast pipe. The cast pipe is attached by threads to the screw shank and rotary union. The length of the cooling hole and the flow rate of water are used to maintain the screw temperature in an optimal range. In general, the cooling hole is drilled into the screw up to the end of the feed section. Two case studies are presented that show flow surging processes that had poor temperature cooling on the feed section of the screw.

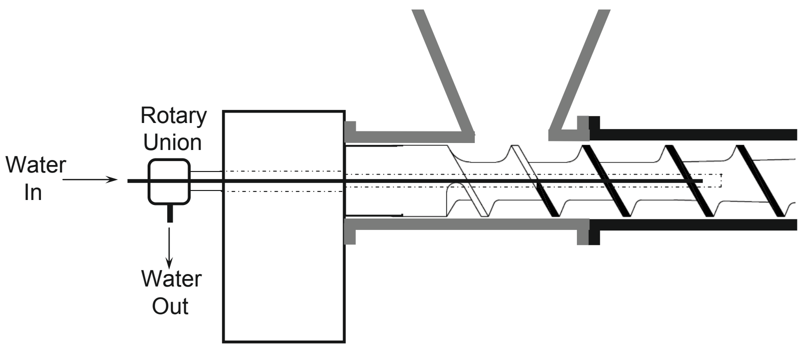

Figure 12.1 Diagram showing a rotary union piping assembly for cooling the feed section of a screw

Two-zone temperature control of the screw has been utilized to mitigate process instabilities in the solids-conveying zone and carbonaceous material buildup on the screw root in the melting zone for polyvinylidene chloride (PVDC) resins [9]. Two-zone screw temperature control can also be used to control the temperature of the solids-conveying zone and energy removal in the metering zone. The control device is similar to that shown in Fig. 12.1 except that a second rotary union is required for the second fluid and a sealing device [10] is needed to isolate the cooling fluids.

12.3.1 Water- and Air-Cooled Barrel Zones

Heating and cooling of the barrel zones is typically done using modules that are equipped with electrical heaters and either water or air cooling. These modules are then clamped onto the outside of the barrel. Water cooling has the capability of removing more energy from the process, and it is well suited for extruders larger

than 150 mm in diameter where the cooling demand is high, that is, where water flows to the modules for 10% or more of the time. If lower levels of cooling are required, however, water cooling can create temperature oscillations in the zone. For example when the zone becomes too hot, the controller will open the solenoid valve to the water flow line for the shortest possible duration. If this minimum amount of water flow is too large, then the cooling on the zone can be too much, causing the temperature of the zone to undershoot the set point temperature [11]. The control scheme will cause the zone temperature to oscillate. Variation in temperature for the barrel zones can affect the rate and discharge temperature. The oscillations can be mitigated by installing metering or needle valves in the water flow lines to reduce the water flow rate to the module. An in-line water filter is typically installed in the cooling line so that the needle valves do not get plugged with particulates.

Air-cooled zone modules do not have the ability to remove as much energy as do water-cooled units. For processes that only require a low level of cooling, air-cooled units will provide a more stable control of the temperature. Recent innovations in air cooling using high-flow fan systems [12] have allowed the replacement of some water-cooled systems with less costly and lower maintenance air-cooled systems [11].

12.4 Rotation- and Geometry-Induced Pressure Oscillations

Pressure transducers that are positioned in the barrel can be extremely useful for troubleshooting a process. Common positions include midway into the melting section and at the entry to the metering section. For two-stage screws, positioning of a transducer at the entry to the second-stage metering section provides information on the degree of fill of the stage and provides knowledge on the likelihood of vent flow. The pressures measured from these transducers provide three types of information: (1) the average pressure in the channel, (2) the pressure variation in the angular direction due to the rotating screw, and (3) the stability of the process by comparing the pressure oscillations during several screw rotations. The pressure in the angular direction is composed of two pressure components: (1) a pressure component in the downstream direction, $\partial P / \partial z$, and (2) the cross-channel pressure gradient, $\partial P / \partial x$. The shape of the angular pressure profile depends on the magnitudes of the components. In order to measure the pressures during rotation, high-speed data acquisition equipment is required. For example, a screw that is rotating at a speed of 60 rpm will require a data acquisition frequency of at least

20 Hz, providing 20 pressure measurements per rotation. Typical pressure measurements for transducers positioned in melting sections and metering sections that are filled with molten resin are shown in Fig. 12.2.

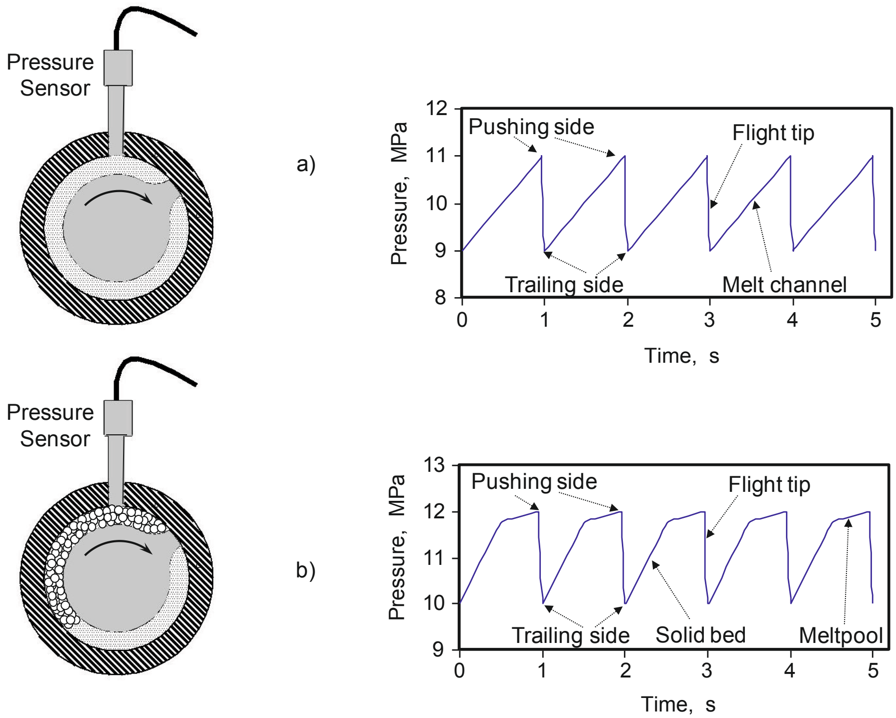

Figure 12.2 Typical pressure measurements for transducers positioned in the barrel for a screw speed of 60 rpm and a positive downstream pressure gradient ($\partial P / \partial z > 0$): a) for a transducer positioned in a metering section where the resin is completely molten, and b) for a transducer positioned in a single-flighted melting section

The pressure profile shown in Fig. 12.2(a) is for a constant-depth metering channel that is completely filled with molten resin, a screw speed of 60 rpm, and a positive downstream pressure gradient ($\partial P / \partial z > 0$); five rotations are shown. The pressure is the highest at the pushing side of the channel and the lowest at the trailing side of the channel. The pressure typically increases nearly linearly with rotation from the trailing side of the channel to the pushing side. As the flight tip passes underneath the transducer, the pressure decreases quickly to that of the trailing side of the channel. Figure 12.2(b) shows a similar pressure profile with rotation in a conventional melting section. For this case, the solid bed extends across about 50 % of the channel. The pressure profile is similar to that for the metering channel case except that the pressure gradient in the region over the solid bed is higher than that for the melt pool. The width of the molten resin can be estimated by the time fraction that the transducer spends over the melt pool and solid bed.

The pressure profiles with rotation shown in Fig. 12.2 are ideal. In practice the pressure profiles contain a level of measurement error and unsteady-state behavior. Pressure in an actual channel operating at a screw speed of 30 rpm for an ABS resin is shown in Fig. 12.3.

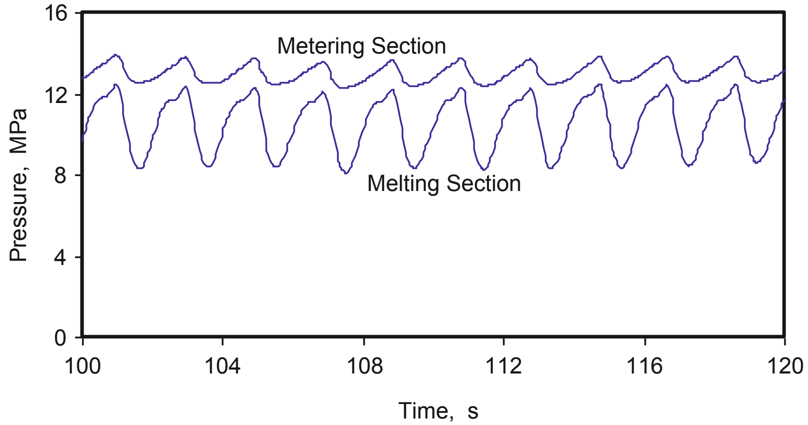

Figure 12.3 Measured pressure profiles with rotation for a 63.5 mm diameter extruder running an ABS resin at 30 rpm, a conventional single-flighted screw, and with a positive downstream pressure gradient in the metering section ($\partial P / \partial z > 0$)

As shown in Fig. 12.3 for the metering channel, the highest pressure is at the pushing side of the channel and the lowest is at the trailing side of channel. The angular pressure profile in the melting section was typical and very similar to the ideal profile shown in Fig. 12.2 because properly operating melting sections have positive pressure gradients in the downstream direction. The data in Fig. 12.3 clearly shows that a level of measurement noise and unsteady-state activity is occurring in the process.

12.5 Gear Pump Control

Gear pumps are often positioned between the extruder and the die, and they provide several processing advantages. These advantages include the mitigation of pressure and flow surges from the extruder, a decrease in the discharge temperature by generating the pressure for the die by the pump instead of the extruder, and by decreasing the discharge pressure via the pump, a capacity increase is possible [13]. For gear pump assisted extrusion, the extruder control algorithms are set to maintain a constant pressure to the inlet side of the pump. The pump is operated at a constant rotational speed, and thus it delivers molten polymer at a very steady and controlled rate. A schematic of a gear pump assisted extrusion

process is shown in Fig. 12.4. If the pressure to the inlet of the pump is less than the set point value, then the control system will increase the screw speed of the extruder. Conversely, if the inlet pressure is too high, the control system will decrease the screw speed. Thus, processes that use a gear pump downstream of an extruder can show large variations in the screw speed in an attempt to compensate for an extruder that is flow surging.

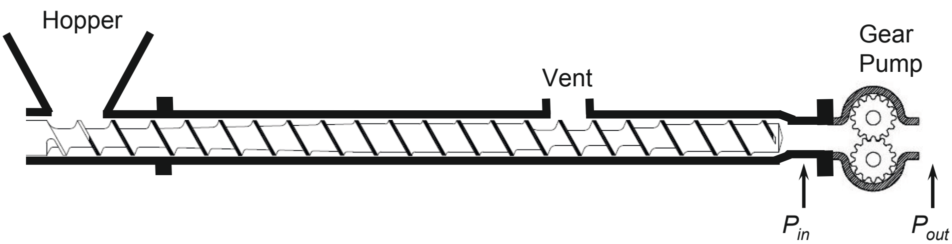

Figure 12.4 Schematic of a two-stage extruder with a downstream gear pump

A poor control algorithm for the pump can cause some variation in the extruder screw speed, causing large variations in the inlet pressure to the pump. This type of control-induced surging can occur even though the process as designed is inherently stable. To determine if the control algorithm is inducing the surging, the screw speed of the extruder should be operated in a manual mode and at a constant speed. If the controller is inducing the surging, placing the process in manual-control mode will stabilize the process. Transient process data were collected for an extruder with a downstream gear pump, as shown in Fig. 12.4. For this case, the control algorithm was controlling the speed of the screw such that the inlet pressure to the pump was maintained at 8 MPa. Although the variation in screw speed was not excessive at 67±1.5 rpm, the variation in motor current seemed quite high at 540±90 A. At about 16 minutes into the run, the extruder was switched from automatic to manual screw control; the screw speed was held constant at 67 rpm. As shown by the data in Fig. 12.5, the motor current variation was unchanged, indicating that the screw speed control algorithm was not inducing the variation in the motor current. During the period that the screw speed was held constant, the pressure to the inlet of the pump slowly increased, as shown in Fig. 12.6. This pressure was increasing because the screw was operating at a speed that delivered a rate slightly higher than that needed by the pump. When the control was placed back into automatic mode, the screw speed was decreased initially to compensate for the higher than desired inlet pressure. This type of analysis is recommended when minor levels of flow surging are observed with a process where the screw speed is controlled from the inlet pressure of a gear pump.

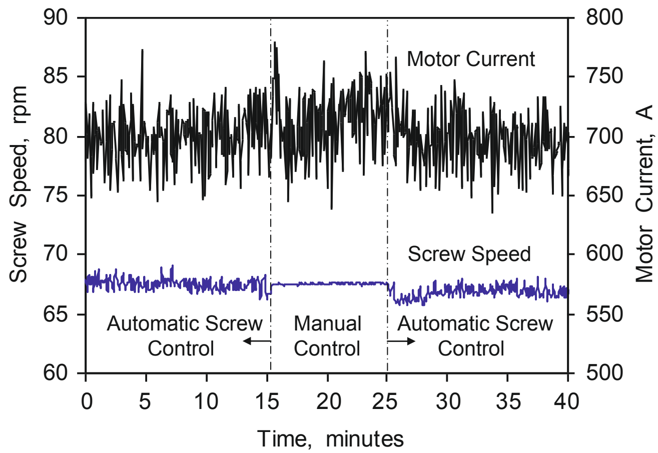

Figure 12.5 An extrusion process with a downstream gear pump with the screw operating in inlet pressure control and followed by the screw in manual operation (constant screw speed). The large level of variation in the motor current during constant screw speed control suggests that the extruder process is unstable, and the control algorithm is not the root cause for the variation in the motor current

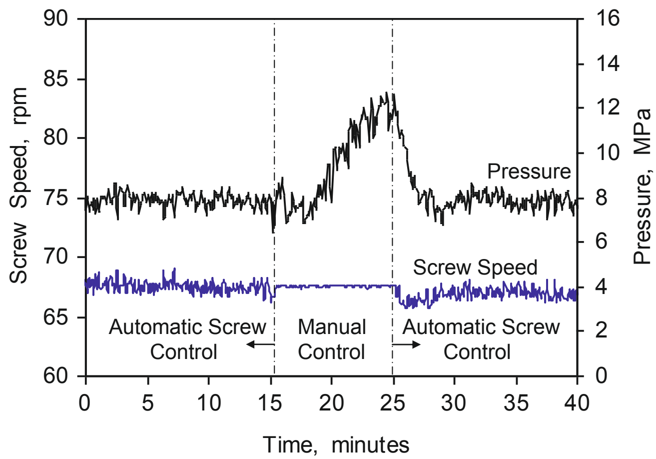

Figure 12.6 Pressure at the inlet to the gear pump for the data presented in Fig. 12.5. The pressure increased during manual control because the flow rate of the extruder was slightly higher than the rate of the pump

12.6 Solids Blocking the Flow Path

Compacted solid polymer fragments can block and restrict the flow in a process. In order for this to occur, two defects typically exist in the process. The first defect causes the compacted solid to fragment and flow downstream in the screw channels. The second defect is a restriction in the channel where the fragments are trapped and accumulated. As the restriction builds, the local pressure just upstream of the restriction will increase while the pressure downstream will decrease. As the downstream pressure decreases, the pressure and rate at the discharge of the extruder will also decrease. The local and high pressure just upstream of the restriction will cause the melting rate of the fragments to increase, temporarily clearing the blockage [2]. When the blockage is removed the rate of the process returns to normal until the next solid fragment blocks the restricted region. Repeated blocking and clearing of the restricted region creates the flow surging.

To eliminate surging due to solid blockages, the troubleshooter must eliminate the defect that caused the solid bed to break up and must also mitigate the restriction in the downstream section of the screw. It is preferred to correct both defects to permanently eliminate surging from the process.

12.7 Case Studies for Extrusion Processes That Flow Surge

Numerous case studies are presented in the next sections that show some common flow surging problems. In these case studies, the problem is presented in a manner that the troubleshooter would encounter during a trial or information-gathering session. Incomplete data and erroneous data are often presented to the troubleshooter. These data were not included here because including them may mislead the reader. The troubleshooter, however, must be able to separate the actual facts of the process from misleading perceptions. In each case study, the modifications required to fix the process are detailed along with supporting fundamental information. In all cases, the rate of the process was limited and the cost to manufacture was high.

12.7.1 Poor Barrel Zone Temperature Control

A 203.2 mm diameter plasticating extruder was running GPPS resin and discharging to a specialty downstream process. Like most processes, the downstream equipment required a nearly steady supply of molten polymer. For this case, the

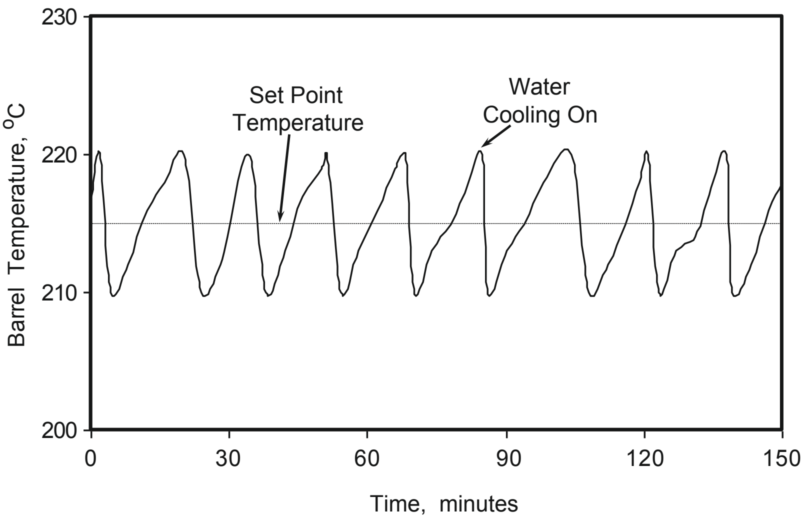

Figure 12.7 Barrel temperature data for a 203.2 mm diameter extruder running GPPS resin and with water cooling on the barrel heating and cooling. This extruder was configured with a water-cooling capability that was too high for the process

barrel zones were electrically heated and water cooled. The barrel zone temperature is shown in Fig. 12.7. The barrel heater for this zone was only used during startup. Once the extruder was operating, the energy dissipation from the screw to the resin was more than enough to keep the section hot. In fact, in order to maintain the zone at the set point temperature of 215 °C, the extruder was operated with a very small amount of barrel cooling. At the low-temperature portions of the cycle, both heating and cooling were off. The small amount of excess energy dissipated in the screw channel was causing the barrel temperature to increase slightly with time. When the temperature exceeded 220 °C, the control algorithm took action and opened the solenoid valve on the water line upstream of the heating and cooling barrel jacket, as shown in Fig. 12.8(a). The controller opened the solenoid valve for the minimum amount of time, sending a short burst of water to the zone. The water would flash evaporate in the unit and then quickly cool the barrel to about 210 °C. Since the solenoid was opened for the shortest possible amount of time, the level of cooling that was utilized was the minimum. It was very obvious that the level of cooling water to this barrel zone was too high for this process. The barrel temperature oscillations shown in Fig. 12.7 were enough to cause a small variation in the product dimensions. Although the variations in the product dimensions were acceptable, the variations did reduce the profitability of the process by causing too much resin to be used in the final product.

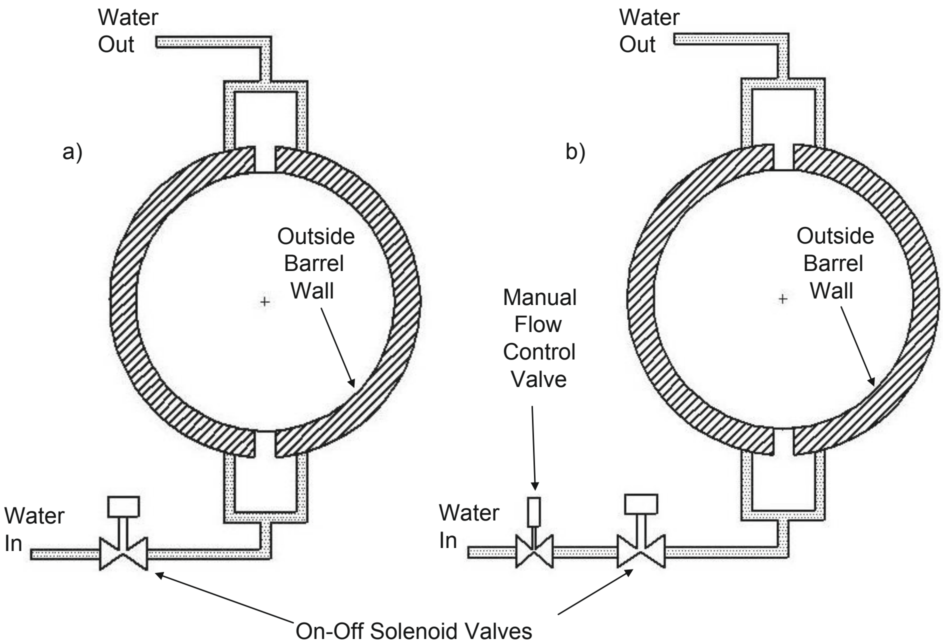

Figure 12.8 Heating and cooling system on the barrel: a) schematic of the original configuration that created the temperature oscillations in Fig. 12.7 and b) a better configuration that minimized the temperature oscillations

In order to reduce the cooling level to the barrel zone, a metering valve was placed in the water line upstream of the solenoid valve as shown in Fig. 12.8(b). Now when the controller opens the solenoid valve, a much lower quantity of water and thus cooling is available to the barrel zone. Prior to this modification, the barrel temperatures oscillated ±10 °C about the set point temperature. After the modification, the temperature oscillations were reduced to about ±3 °C, and the profitability of the process was improved due to the minimization of resin consumption.

This temperature control problem occurred due to the implementation of a high-performance-type screw. The original screw was fabricated with a relatively shallow metering channel. The shallow channel had a low specific rate and also dissipated a relatively high level of energy. The excess energy was easily removed through the barrel wall with the water cooling using the configuration shown in Fig. 12.8(a). That is, the solenoid valve was in the open position enough to maintain cooling while not causing the barrel temperature to undershoot the set point temperature. The high-performance screw, however, was designed with a deeper metering section, had a considerably higher specific rate, and dissipated less energy. For this screw, less excess energy needed to be conducted through the barrel wall. Since the cooling system was designed for a process with a high heat flux through the barrel, the temperature became very oscillatory when the energy flux was reduced when the high-performance screw was implemented.

This simple case study shows the importance of verifying the control algorithms before proceeding with a troubleshooting trial. Before any testing or equipment modifications are performed, it is extremely important to have a deep understanding of the process and have all process controls and sensors in acceptable operation. If the sensors and controls are not functioning properly, then the troubleshooter may modify the wrong section of the process and obtain little to no improvement in the process.

12.7.2 Optimization of Barrel Temperatures for Improved Solids Conveying

Numerous complaints were logged by a single processor from several different manufacturing plants on flow surging and reduced rates for a specialty resin. The flow surging caused unacceptable variations in the final product. In all cases small-diameter extruders were used, but the operating conditions reported were different in the plants. In several of the plants, there were some extruders that did not flow surge, yet the design of these machines appeared to be identical to those that experienced flow surging. It was not apparent why some of the extruders were operating well while others were surging.

An extrusion trial was performed at the processor's plant using a 38.1 mm diameter production extruder, a proprietary screw design, and resin that had previously exhibited flow surging and reduced rate. The extruder was equipped with three barrel zone heaters with control thermocouples (labeled T1, T2, and T3) and two pressure sensors. One pressure sensor was located in the midsection (zone 2) of the barrel (P2) and the other at the end of the barrel near the tip of the screw (P3). Both transducers were positioned over the top of the screw such that a pressure variation due to screw rotation would be observed.

During the trial, process data were collected from each sensor at a frequency of once every 10 seconds using a portable data acquisition system. For barrel zone temperatures of 150, 163, and 174 °C for zones T1 through T3, respectively, the extruder was operating stably and at rates that were consistent with numerical simulations, and it was producing a high-quality product. Process data for steady-state operation are shown in Fig. 12.9 for a screw speed of 50 rpm. As indicated by this figure, the barrel zone temperatures were steady and only small variations occurred for the P2 and P3 pressure sensors. Slight pressure variations were expected for this extruder because the sensors were positioned in the barrel and were measuring pressure in different regions of the channel as the screw rotated. The pressure patterns are not periodic like those in Fig. 12.3 due to the screw speed and acquisition rate used. For this case, pressure samples were collected every 8.3 rotations. A faster data collection rate would have shown a periodic oscil-

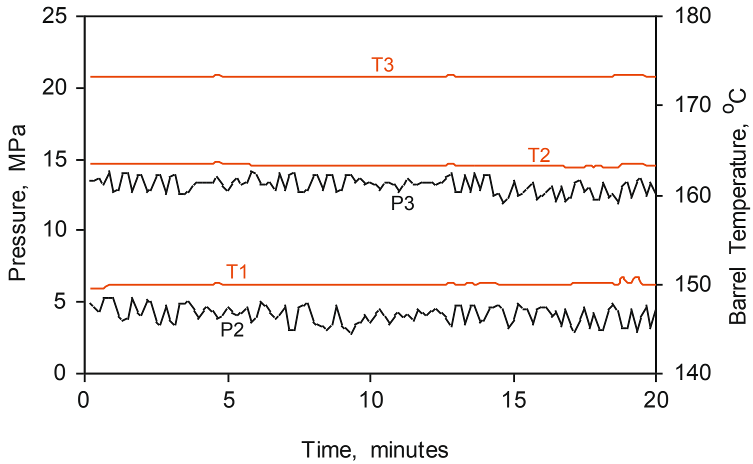

Figure 12.9 Barrel pressures and temperatures for the 38.1 mm diameter extruder operating stably. The temperature profiles are in red while the pressures are black

lation of the pressure. These data indicate that conditions exist for the stable processing of the resin.

For a second experiment, the extruder was operated at barrel set point temperatures of 160, 163, and 174 °C for zones T1 through T3; the zone T1 temperature was increased by 10 °C, and zones T2 and T3 temperatures were unchanged. This increase in the T1 temperature caused the extruder to flow surge and decreased the rate by about 20 %. The process data for the unstable conditions are shown in Fig. 12.10. As indicated by this figure, the pressure for the midbarrel pressure sensor, P2, was zero during the low pressure swing of the cycle, indicating that this portion of the channel was operating partially filled (or starved). Later in the experiment, the pressure sensor responses were checked when the pressure was known to be zero in the channels. The pressure was measured by the sensors at 1.4 MPa when the pressure was actually zero, explaining the offset pressure at the bottom of the pressure cycle in Fig. 12.10. Numerical calculations and a Maddock solidification experiment confirmed that the midsection of the extruder was operating partially filled. Thus, a small 10 °C increase in the first barrel zone temperature was enough to cause the extruder to go from operating as a stable process producing high-quality product to one that was unstable with reduced rates and having a product with unacceptable product dimensions. Numerous other experiments had shown that the first barrel zone temperature needed for stable extrusion depended on the screw speed and the temperature of the feed resin. Moreover, the processor indicated that flow surging was experienced for some extruders at zone T1 barrel temperatures as low as 148 °C.

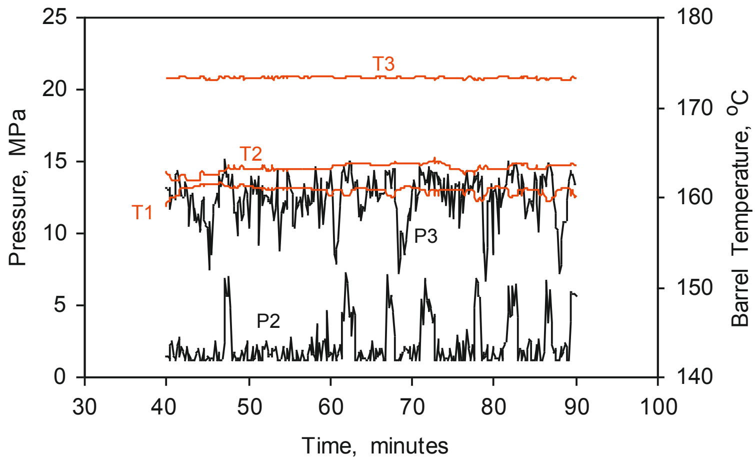

Figure 12.10 Barrel pressures and temperatures for the 38.1 mm diameter extruder operating at a zone 1 barrel temperature condition that caused the extruder to flow surge. The temperature profiles are in red while the pressures are black

Based on the data collected, the Maddock solidification experiment, and the numerical calculations, the problem was diagnosed as poor solids conveying from improper temperatures in the section. Slight differences between extruders, such as the axial and radial position of the zone T1 thermocouple, barrel zone controller tuning, screw geometry variations, and thermocouple accuracy likely caused conditions such that some of the extruders flow surged while others did not. These minor variations could influence the temperature of the inside barrel wall of the solids-conveying section. Moreover, different rate requirements for different products required that the extruder be operated at different screw speeds, which further complicated the solids-conveying problem. The problem could have been avoided if plant personnel had optimized the barrel temperatures for each extruder using the technique described in Section 10.9.

12.7.3 Flow Surging Due to High Temperatures in the Feed Section of the Screw

A severe and random flow surging problem limited the production rate for a large-diameter, two-stage, vented extruder. If it were not for a gear pump positioned between the extruder and die, this extrusion line would not have been operable. The surging did, however, limit the output of the line to about 70 % of its potential rate. The maximum potential rate is the rate that the extruder can run at high screw speeds and with proper operation. The extruder was 203.2 mm in diameter and had a 40 *L/D* barrel. A schematic for the extruder and gear pump arrangement is shown in Fig. 12.11, and the screw channel dimensions are provided in

Table 12.1. The specific rotational flow rate for the first-stage metering section was calculated at 20.0 kg/(h·rpm). The extruder was fed a mixture of fresh HIPS resin with 30 to 60 % recycled ground sheet from a downstream thermoforming process. The level of recycle affected the bulk density of the feedstock entering the extruder. The HIPS resin had an MFR of 3.9 dg/min (230 °C, 5.0 kg). The screw was single-flighted and typical of what is used for HIPS resins. Screw temperature control was accomplished by flowing cooling water through a rotary union into and out of a hole cut into the feed end of the screw as shown in Fig. 12.1. This hole extended 3.8 diameters into the feed section. Pressure sensors were positioned in the barrel wall at the end of the first-stage transition section (P1), at the end of the first-stage metering section just before the vent (P2), and at the discharge. Additional pressure sensors were positioned at the discharge of the extruder and at the inlet (suction side) to the gear pump. A screen filtering system was positioned between these pressure sensors as shown in Fig. 12.11. A commercial control scheme adjusted the screw speed to maintain a constant pressure of 9 MPa to the inlet of the gear pump. The gear pump was operated at constant speed in order to maintain a constant flow rate of material to the die.

Table 12.1 Screw Channel Dimensions for a 203.2 mm Diameter Two-Stage Vented Screw Running HIPS Resin

	Depth, mm	Length, diameters	Notes
Feed section	28.6	7	The compression ratio was 4.0 and the compression rate was 0.0032
First-stage transition		10	
First-stage meter	7.1	8	
Vent section	31.9	4.5	The pump ratio was 1.7
Second-stage transition		3.5	
Second-stage meter	12.3	6	
Lead length, flight width, and flight clearance were 203.2, 23.9, and 0.20 mm, respectively, in all sections of the screw. A 28.7 mm diameter screw cooling hole was drilled in the shank end of the screw, and it extended 3.8 diameters into the feed section. The first 2.5 diameters of the screw were inside a water-cooled feed casing. The specific rotational rate of the first-stage metering section was calculated at 20 kg/(h·rpm).			

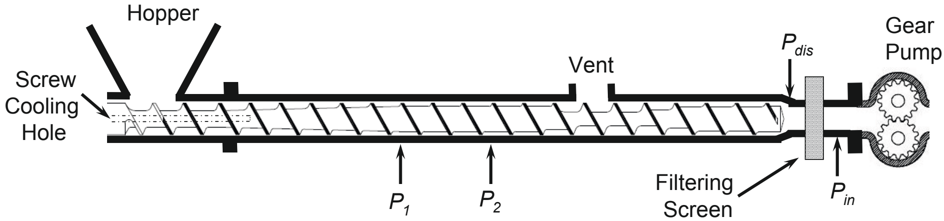

Figure 12.11 Schematic of the 203.2 mm diameter extrusion process for HIPS resin

In order to diagnose the problem, a data acquisition system was temporarily connected to the extrusion panel. All available sensor outputs were connected in parallel with the acquisition system. Electronic data were collected at a frequency of once every 9 s. Steady-state operation of the extruder is shown by the first 400 minutes in Figs. 12.12, 12.13, and 12.14. The data for these figures were from the same production run. The extruder was running at 2250 kg/h and a screw speed of 99 rpm for a specific rate of 22.7 kg/(h·rpm). This specific rate is about 14 % higher than the specific rotational flow rate calculated for the first-stage metering section, indicating that a negative pressure profile exists in the section. The negative pressure gradient is expected for a first-stage metering section of a vented screw that is operating properly; that is, the first-stage metering section was full of resin. To maintain the stability, the extruder screw speed was reduced such that the extruder was operating at about 70 % of its potential maximum rate. That is, at screw speeds higher than 99 rpm the extruder was more likely to transition from a stable to an unstable operation. The barrel pressure at the end of the first-stage transition section, P1, had variations of about ±3 MPa about the average pressure. This pressure variation was considerably higher than expected and suggests that the extruder, although running stably, was on the verge of unstable operation. Some of the variation was due to the movement of the flight tip past the sensor. Barrel zone temperatures tracked the set point values and were stable.

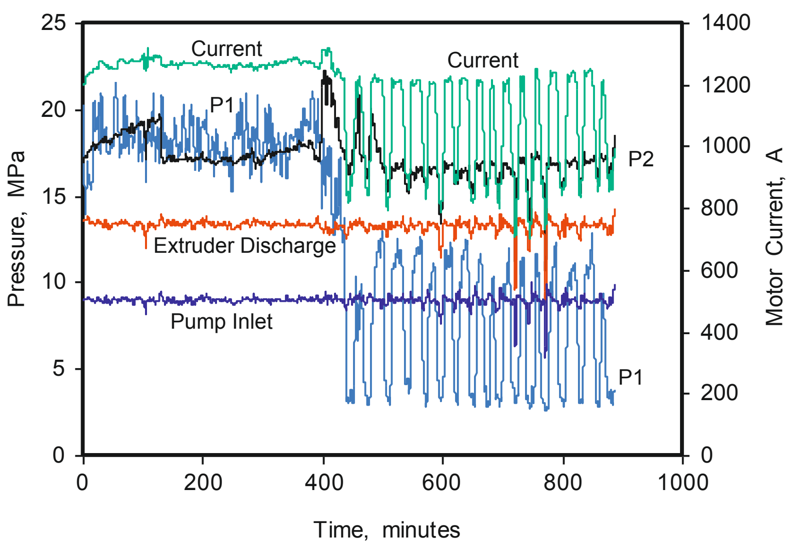

Figure 12.12 Barrel, discharge, and pump inlet pressures and motor current for stable and unstable extrusion for a large-diameter extruder running HIPS resin

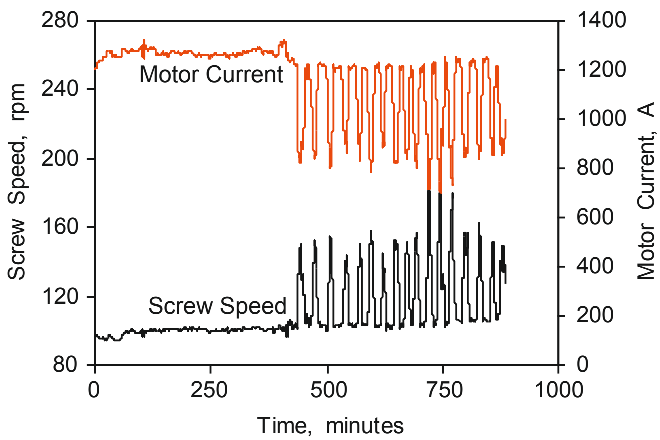

Figure 12.13 Screw speed and motor current for a large-diameter extruder running stably and unstably

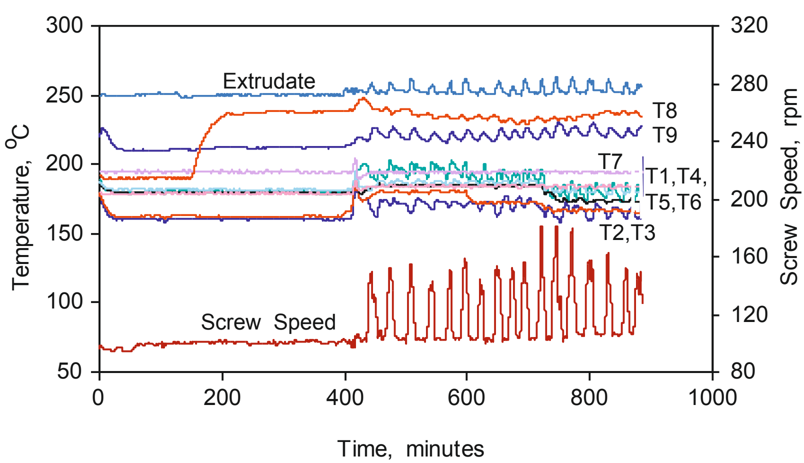

Figure 12.14 Screw speed, extrudate temperature, and barrel zone temperatures for a large-diameter extruder running stably and unstably

At about 410 minutes into the run, the extruder started to operate unstably, as indicated in Figs. 12.12, 12.13, and 12.14. The processing change that caused the extruder to go from a stable operation to an unstable one was not known, but it could have been due to minor changes in the bulk density of the feedstock or cooling water fluctuations to the screw. As indicated by these figures, the event started when the P1 pressure decreased slightly, causing the rate and the P2 pressure to decrease. This decreased pressure transmitted down the extrusion system, eventually decreasing the pressure at the inlet to the gear pump. To correct for the lower pressure, the controller on the gear pump increased the speed of the screw from 99 rpm to about 160 rpm. Next the P1 pressure increased due to the higher

screw speed and higher flow rate, as indicated in Fig. 12.12. As the pressure increased at the gear pump inlet, the gear pump controller decreased the screw speed back to about 100 rpm, causing the extruder to flow surge. Flow surging caused the screw speed controller to oscillate about once every 25 minutes. As indicated in Fig. 12.12, the screw speed controller was able to provide a relatively stable pressure to the pump inlet, allowing the process to run at reduced rates. The barrel zone temperatures, as indicated in Fig. 12.14, were extremely oscillatory.

As indicated in Fig. 12.12, the P1 pressure was considerably lower during the period of unstable operation. This result indicates that the cause of the problem originated in the first stage of the screw before the first-stage metering section. At a screw speed of 160 rpm, the extruder was still operating at a rate of 2250 kg/h, but the specific rate decreased to 14 kg/(h·rpm). This specific rate is considerably less than the specific rotational flow rate of 20 kg/(h·rpm), indicating that the first-stage metering section was operating improperly and only partially filled. The most likely reason for a partially filled or starved metering section was poor solids conveying from the feed section to the transition section. Poor solids conveying was likely due to improper temperature control of the metal surfaces in the feed section of the extruder and screw. Barrel feed zone heaters, controllers, and the feed casing were examined and determined to be operating properly at set point temperatures typically used for HIPS resin. Based on this information, the investigation was focused on the temperature control of the screw.

It was hypothesized that the screw temperature in the feed section was too hot to convey solids effectively to downstream sections of the screw. To test this hypothesis, the effect of internal screw cooling was determined during a period when the extruder was operating stably. For this period, cooling water was flowing to the screw-cooling device, and the extruder was operating stably and properly at a rate of 2360 kg/h and a screw speed of about 104 rpm. The metal surface temperatures of the pipes used to flow water into and out of the screw were measured at 29 and 37 °C, respectively. At about 28 minutes into the run, the cooling water flow to the screw was turned off, as indicated in Figs. 12.15 and 12.16. At about 30 minutes, the pressure at the end of the first-stage transition section, P1, started to decrease as shown in Fig. 12.16, indicating that solids conveying was significantly reduced. Like before, the reduced solids flow caused the downstream pressures to decrease and ultimately to cause the extruder to flow surge. At about 36 minutes into the run, cooling water flow was turned on, and within about four minutes the extruder operation became stable, as indicated in Figs. 12.15 and 12.16. The surface temperature of the pipe for water flow out of the screw was measured at 81 °C just after the cooling water was turned on, a temperature change of 44 °C. As will be presented later in this section, solids conveying of HIPS resin becomes difficult or unstable at screw temperatures of about 150 °C and higher. The temperature of the screw surface was unknown, but it likely increased by at least 44 °C and possibly approached 150 °C.

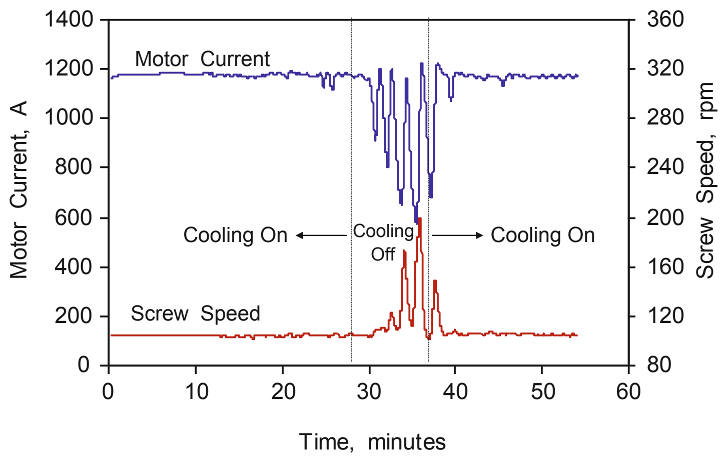

Figure 12.15 Screw speed and motor current for the screw cooling experiment

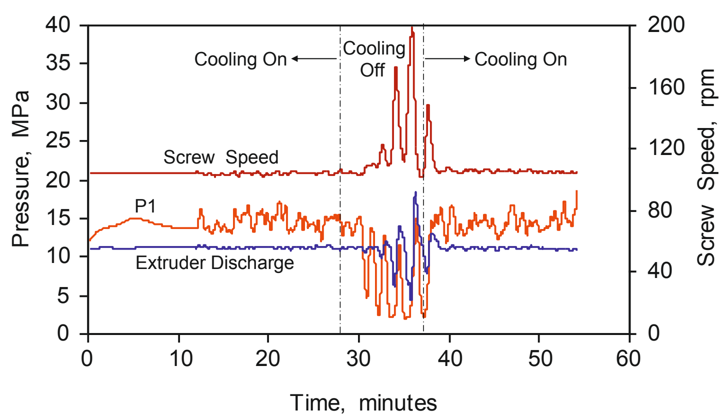

Figure 12.16 Screw speed, pressure at the entry to the first-stage meter (P1), and discharge pressure for the screw cooling experiment

Based on the above data, the cause of the extrusion instability was identified as high temperatures on the screw surfaces of the feed section. These high surface temperatures caused the coefficients of dynamic friction to increase, increasing the retarding forces on the solids at the screw surface. Since solids conveying depends on a combination of forwarding forces at the barrel wall and pushing flight and retarding forces at the screw root and trailing flight, an increase in the retarding forces will cause a reduction in the solids-conveying rate. The instability appeared to be random due to the complicated interactions of cooling water flow rate and temperature and due to changes in bulk density of the feedstock.

Several technical solutions were considered to increase the cooling level to the feed section of the screw, including increased water flow and the use of chilled water. The best technical solution and quickest to implement was to increase the

length of the cooling hole in the screw. The length of the cooling hole was increased from 3.8 diameters into the flighted section to 7 diameters up to the end of the feed section. After the screw modification, the extruder has not experienced instabilities of this type, and the rate has increased to 100 % of its maximum potential rate.

Cooling on the screw and feed casing are often limited by the water pressure at the supply and discharge sides. That is, if the water pressure on the discharge header is nearly the same as that of the supply side, then the water flow rate will be very low due to the lack of a pressure driving force. Thus, if the driving pressure for water flow is not available then adequate cooling to the screw and casing may not exist. A simple way to test if the cooling water flow is acceptable is to disconnect the discharge water line from the header and either flow this water to a drain or the parking lot using a temporary hose. The discharge water flow should be high and the temperature should be warm to the touch. A permanent arrangement might consist of a water pump and a rotameter in-line upstream of the rotary union attached to the screw.

To aid in the understanding of this solids-conveying problem, the coefficient of dynamic friction was measured for the resin as a function of temperature and sliding velocity at a pressure of 0.7 MPa. The equipment used to make the measurement is described in Section 4.3.1 and is shown in Fig. 4.11. Since the coefficient of dynamic friction is only defined for solid-state processes, the friction values are reported here as stress at the interface because the stress can be described from ambient temperatures up to processing temperatures. The shear stress at the interface for HIPS resin is shown in Fig. 12.17 at a pressure of 0.7 MPa. As indicated by this figure, the shear stress was nearly constant from ambient temperature up to about 110 °C, increased to a maximum stress near 150 °C, and then decreased as the temperature was increased further. Optimal performance of the solids-conveying section for this resin would be such that the forwarding forces are maximized with metal surface temperatures near 150 °C where the stress is a maximum, and the retarding forces minimized with metal surface temperatures of 110 °C or lower. Thus, optimal solids conveying for HIPS resin would occur with a feed zone barrel inner surface temperature near 150 °C and a screw surface temperature in the feed section no higher than 110 °C. In practice, screw temperatures less than 90 or 100 °C are preferred such that melting of the resin does not happen if an emergency shutdown should occur. For the solid state temperature region, the shear stress at the interface can be converted to the coefficient of dynamic friction by the following:

$$f = \tau / P \tag{12.4}$$

where f is the coefficient of dynamic friction, τ is the shear stress at the polymer-metal interface, and P is the pressure (0.7 MPa in this case).

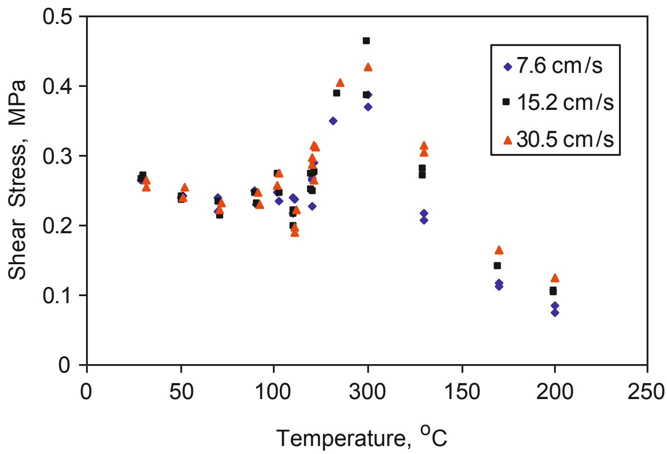

Figure 12.17 Shear stress between HIPS resin and a metal surface at a pressure of 0.7 MPa and as a function of temperature and sliding velocity

12.7.4 Flow Surging Due to High Temperatures in the Feed Casing

The extruder described in Fig. 12.11 on a different occasion started to flow surge but with a slightly different frequency, as shown in Figs. 12.18 and 12.19. As indicated in these figures, there were short time periods when the discharge pressure and screw speed were stable and the motor current was high. During these periods, the extruder was operating well but at a reduced production rate. During periods of unstable operation, the motor current decreased by about 20%, the screw speed increased, and the discharge pressure became extremely oscillatory. Like the previous case, as the motor current decreased solids conveying decreased, causing the controller to increase the speed of the screw.

During the trial, the feed casing to the extruder had an outside surface temperature of about 80 °C. Although not measured, the inside cylinder wall of the feed casing for the first 1.5 diameters downstream of the feed opening was considerably hotter. These higher temperatures were caused by a combination of frictional heating of the solids on the wall and also by conduction from the first heated zone of the barrel. It is estimated that temperatures as high as 170 °C occurred in the feed casing. As presented in Section 12.7.3, optimal solids conveying will occur when the stress at the polymer-metal interface at the barrel is a maximum, and for HIPS resin this surface temperature is near 150 °C. Surface temperatures higher than 150 °C in the feed section will reduce conveying and lead to starving of the screw channels and ultimately flow surging. Corrosion inside of the cooling channels of the feed casing prevented the flow of cooling water. Cleaning the cooling channels and adding a larger cooling water recirculation pump reduced the temperature of the feed casing and eliminated the flow surging problem.

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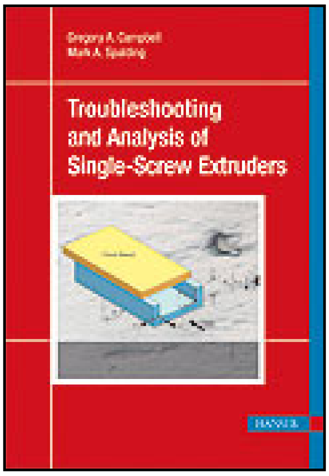

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